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THE LARGE SPACE STRUCTURES
TECHNOLOGY PROGRAM

APRIL 1992

ROBERT W. GORDON

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This report describes an in-house exploratory development project in the dynamics and control of large space structures. The program was conducted as a series of experiments on test articles dynamically similar to large space structures. The program concentrated on two technical areas; ground testing and active vibration control. Several experiments are described that developed and applied methods for the simulation of zero-gravity environment of space in a ground test. The ground test series was culminated by a reduced gravity flight test of a 12-meter truss structure. Several experiments are also described in the active feedback control of vibration in test structures ranging from cantilevered beams to a large truss beam.

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FOREWORD

This report describes work performed at the Wright Laboratory, Flight Dynamics Directorate, Structures Division, Structural Dynamics Branch from July 1985 to December 1991. The work was directed by Robert W. Gordon (WL/FIBGC) as Project Engineer under Project 2401, "Structural Mechanics," Task 04, "Vibration Prediction and Control, Measurement and Analysis," Work Unit 24010432, "Large Space Structures Technology Program."

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1.0 INTRODUCTION

Large space structures, in the form of surveillance systems, directed energy weapons or space platforms will play a key role in the Air Force of the future. Many of these systems will have formidable dynamic precision requirements in terms of shape control, line-of-sight jitter and settling time after retargeting. The Structures Division of the Wright Laboratory is a leader in developing technology for dynamic analysis and testing of tomorrow's aerospace structures and in the 1980s was committed to strengthening its capability in these areas for large space structures.

In 1985, the Structures Division established an in-house exploratory development program entitled Large Space Structures Technology Program (LSSTP) to achieve this improved capability. This program addressed two major areas in large space structures dynamics and control: 1) design and analysis methods for predicting dynamics of large, flexible structures with passive damping and active vibration control and, 2) earth based testing of these structures to include zero-gravity simulation, excitations approaches, data acquisition, sensors and actuators, and implementation of passive damping and active vibration control.

1.1 <u>Scope</u>--This report summarizes all activity performed under the in-house LSSTP. The report is divided into sections covering introduction, program organization, modal testing and zero-gravity simulation, active vibration control, facility and equipment improvements, and conclusions. This report also provides a bibliography of reports, papers and presentations generated under LSSTP as well as all of the people who participated in the program over its five and a half year duration.

1.2 <u>Objective and Approach</u>--The objective of the LSSTP was to establish a capability in the Structures Division for the analysis and testing of large space structures (LSS) with passive damping and active control systems. This program would provide Wright Laboratory personnel with a solid foundation for contracted research in LSS dynamics and also advance the technology base in analysis techniques, active vibration control approaches and ground test methods. The approach was to conduct a series of experiments, from simple to complex, on dynamically realistic structures.

1.3 Background--In the mid-1970s, the Air Force and NASA began investing in the development of large space structures. Many types of systems including antennas, telescopes, platforms and weapons were proposed and studied. Unlike all satellites before this time, these new systems would be relatively flexible. In addition, they would possess ultra-stringent performance requirements in terms of shape control, line-of-sight pointing or settling time after maneuvers. The combination of increased flexibility with more stringent dynamic performance requirements created extreme challenges for structural dynamics and control technology. These large, flexible structures would have many low frequency, closely space vibration modes which would interact with the attitude control system giving birth to the control-structure interaction problem. Traditional means of vibration control by increasing stiffness would result in unacceptable weight increases. Optimal integration of passive damping and active vibration control would be required. In addition, the experimental testing and identification of the dynamic characteristics of these structures for control design and performance prediction was very challenging.

During the same time period, the Air Force, NASA, and DARPA (and later, the SDIO) began investigating the dynamics and control technology required to meet the challenges just described. The DARPA-sponsored Active Control of Space Structures (ACOSS) program pioneered the development of active vibration control technology for large space structures. The Air Force and SDIO Passive and Active Control of Space Structures (PACOSS) program built on the ACOSS controls work by demonstrating the synergistic benefits of passive damping with active control. The Air Force programs in Vibration Control of Space Structures (VCOSS and VCOSS II) performed some of the first practical experiments in active vibration control for space structures. NASA also began in-house and contract work in ground test methods and active controls with the Control of Flexible Structures (COFS) program. The in-house LSSTP was initiated to build on the results of these programs to achieve the stated objectives.

2.0 PROGRAM ORGANIZATION

The Large Space Structures Technology Program (LSSTP) was initiated in mid-1985 as a Structures Division-wide in-house project with emphasis on experimentation. The original program plan was aggressive, and the project team assembled to perform it was large and diverse. This section describes the project organization and plan as it was originally envisioned and how the plan evolved over the life of the project to accomplish the objectives.

Initial Organization and Plan--The LSSTP was initiated in July 1985. It was conceived by Jerome Pearson, who, as leader of the Vibration Group, was responsible for several contracted efforts in active vibration control for space structures. The program was originally planned with 6 phases. The first phase was development of facilities, equipment and procedures for ground testing and active vibration control of experimental structures. The remaining 5 phases comprised a series of experiments, increasing in complexity, designed to investigate ground testing and active vibration control. Phase II was the Tetrahedral Truss active control experiment designed to apply active vibration control approaches to the ACOSS model no. 1 structure [1]. Phase III was the 40-foot Truss Experiment which was to investigate passive damping and active control on a pair of 40 foot long trusses. Phase IV was the Control of Flexible Structures (COFS) 1/5-Scale Mast experiment which was to develop and evaluate passive damping and active control approaches on a 1/5-scale model of the 60 meter mast truss being developed on a NASA contract. Phase V was the Slewing Experiment which would investigate the dynamics and control of a large angle slewing structure. Finally, Phase VI was the Large Space Structure Experiment which was to pull together all the technologies previously studied in one large, complex test article. The original LSSTP schedule is shown in Figure 1.

A multi-disciplined team was formed to conduct the program. The team was made up of people from all branches in the Structures Division and the Control Design Branch of the Flight Control Division. Jerome Pearson was named project manager and Terry Hertz from the Analysis and Optimization Branch was his deputy. The technical disciplines and the team members providing them are shown in Figure 3 along with their branch affiliations.

The LSSTP had considerable momentum and management support when it was formed. The team held meetings at least bi-weekly with nearly all team members attending. Col Roger Hegstrom, chief of the Structures Division, was instrumental in establishing the program. Initially, briefings to the FIB branches chiefs were to be held bi-weekly. Program activities were coordinated frequently with NASA Langley and Marshall Research Centers, the Air Force Astronautics Laboratory (now a part of Phillips Laboratory) and contractors. The program also had considerable funding. The original budget had $125K in FY86, $500K in both FY87 and FY88, and $200K in FY89 and FY90. These funding numbers were received in every year except FY90, when the allocation was cut to $133K due to general funding cuts in the Flight Dynamics Directorate.

Early in the program, a Memorandum of Understanding (MOU) was established with NASA Langley Research Center to cooperate in the development of dynamics and control technology for LSS. The cooperation revolved around the NASA COFS project, which was ultimately scheduled to test a 60 meter long mast truss on the Space Shuttle Orbiter. The LSSTP involvement was to purchase a 1/5-scale model of the COFS mast and sponsor a contractor to develop and test active vibration control schemes on the model and eventually on the full-scale mast in orbit. Funding and schedule problems delayed and eventually lead to the cancellation of the COFS program. No contracts were ever awarded under LSSTP to support the COFS 1/5-scale mast. However, the requirements for testing the mast drove LSSTP in-house testing requirements and directly benefitted the subsequent 12-meter truss experiments. In addition to the cooperative research, the MOU also established a jointly sponsored controls-structures interaction technology conference, which was held approximately every 18 months from November 1986 through March 1992.

Actual Schedule--The original schedule for LSSTP experiments was very aggressive and was gradually scaled back as the program progressed. Some of the experiments were dropped while others were expanded. Figure 2 shows the schedule of LSSTP experiments as they actually occurred. The Tetrahedral Truss active control experiment proved too difficult to fabricate and was replaced with the Advanced Beam Experiment in 1986. The 40 foot Truss experiment evolved into the 12-meter trusses which became the test beds for several ground tests and a zero-g flight test. The 12-Meter Truss Active Control Experiment was the second active vibration control experiment in the program and made use of the undamped 12-meter truss. The COFS

1/5-Scale Mast experiment was cancelled when NASA cancelled the entire COFS program. The Slewing Experiment was slipped and then dropped due to the considerable effort sponsored by Astronautics Laboratory in the slewing area. Finally, the Large Space Structure Experiment was slipped to early 1991 and was to use the PACOSS Dynamic Test Article. However, in early 1991, Wright Laboratory dropped the mission area of space structures and the experiment was cancelled. The DTA was later given to the Air Force Institiute of Technology for graduate research. This marked the end of the LSSTP.

The gradual scaling back of the LSSTP was primarily due to a general lack of team experience in the structural dynamics and control areas. The available expertise in the control design area was especially a problem. The Flight Controls Division provided part-time people to the program who added a valuable controls perspective, but experienced manpower was needed for experimental controls implementation. To fill the need, a contract was sought with the Electrical Engineering Department of Ohio State University. In late 1986, short-term control design support for the Advanced Beam Experiment was contracted to OSU through a directorate-level task order contract. Then, in late 1987, a direct R&D contract was awarded to them for control testing on the Advanced Beam and for control design and testing on the 12 Meter Truss Active Control Experiment. Professors Ozguner and Yurkovich and several graduate students at OSU provided the valuable controls expertise and manpower. OSU support to LSSTP continued until the end of 1990.

The LSSTP was originally managed by Jerome Pearson, in addition to his responsibilities as Vibration Group leader. Terry Hertz of FIBR was assigned as his deputy on a part time basis. When Terry left the Directorate in early 1986, Bob Gordon of FIBA was assigned as his full time replacement. Mr Pearson was promoted to chief of the Structural Dynamics Branch in mid-1987 and Maj Alan Janiszewski was selected as Vibration Group leader and new LSSTP program manager. In late 1987, Maj Janiszewski stepped down as program manager and named Mr Gordon as his full time replacement. Mr Gordon continued as program manager until the LSSTP ended in 1991.

The list of people who worked on the LSSTP during its 5-plus year life is long. The primary participants came from the Structural Dynamics Branch, especially in the later stages of the program, but significant contributions were made by people from several branches in the Structures Division and the Control Dynamics Branch of the

Flight Control Division. Considerable support was also received from several universities, including Professors Ozguner and Yurkovich and their students at Ohio State University, Professor Don Mittleman of Oberlin College, graduate students from the Air Force Institute of Technolcgy, Rensselaer Polytechnic Institute, Ohio University and Michigan State University and several cadets from the Air Force Academy. Table 1 lists the names and organizations of all people who made contributions to the LSSTP.

3.0 MODAL TESTING AND ZERO-GRAVITY SIMULATION

Much of the effort in the Large Space Structures Technology Program was directed toward evaluating methods for testing large space structures on the ground while simulating the zero-gravity environment of space. Several test approaches were evaluated, including counterbalance suspension, multiple boundary conditions, zero spring-rate mechanisms and parabolic arc aircraft flight tests. The 12-meter trusses were the primary test articles used to evaluate test methods. This section covers the analysis and experiments conducted in the LSSTP to evaluate ground test methods.

Counterbalance Suspension--The counterbalance suspension approach was conceived by Jerome Pearson and Professor Don Mittleman of Oberlin College. The concept was to counterbalance a test article with a second, identical test article by means of cables and pulleys as shown in Figure 4. This approach offered nearly unrestrained vertical motion while the long cables provided low restraint horizontal motion. Professor Mittleman, assisted by Capt Zeigler, performed initial analytical studies and limited experiments on the counterbalance concept [2] in the summer of 1984 as part of the Summer Faculty Research Program at Wright Laboratory. This predated the official start of the LSSTP, but the work continued and was incorporated into the LSSTP. Mittleman continued his analysis of the Atwood's machine, i.e., two counterbalanced masses [3] [4]. He eventually studied more complex configurations including counterbalanced dumbbells and rigid rods, but never reached a solution for flexible beams, which was the primary objective. His work is summarized in [5].

The proof of the counterbalance suspension concept was to show that a properly counterbalanced test article possessed the same dynamic characteristics as the test article alone in zero gravity. For the purpose of the in-house analysis, the counterbalanced article should have the same dynamic characteristics as a single article with free boundary conditions. This proof was made by Gordon [6] with finite element analysis of the vertical plane dynamics of counterbalanced flexible beams. This study showed that a flexible beam counterbalanced by an identical beam through a system of elastic cables and pulleys possessed the same normal mode frequencies and mode shapes as a single beam with free boundary conditions. There would be a small damping contribution from friction in the pulleys. However, the study also showed that the counterbalanced system possessed additional modes not found in the single beam, involving stretching of the elastic cables. It was proposed that these "suspension" modes could be placed in frequency by careful design of the suspension so as not to interfere with structural modes.

Capt Zeigler and others performed experimental work to verify the analyses of Mittleman and Gordon. A series of tests was performed on slender aluminum beams [7] [8] leading up to a full counterbalance test. The test results confirmed the results of Gordon [6]. The system of two nearly identical beams had the same frequencies and mode shapes as a single beam suspended on wires and also possessed a family of elastic suspension modes. It became clear from the experiments that designing a suspension that separated the structural modes from the suspension modes would be difficult for beams and practically impossible for more complex structures. In addition, the counterbalance suspension approach was impractical due to the virtual impossibility of obtaining two identical test articles caused by variations in material properties, joining methods and manufacturing tolerances. Finally, even if the suspension could be "tuned" to avoid structural modes and identical articles could be obtained, the cost of the second test article would be prohibitive in many cases.

Testbed Truss--The Testbed Truss experiment was a simple, 40 foot long truss beam which served as a test bed for evaluating facility requirements and dynamic test methods for the 12-meter trusses investigated later in the program. It was developed as part of Phase I, Large Space Structures Test Facility Development of the original LSSTP program plan. The truss was to be cantilevered from both floor and ceiling mounting fixtures to evaluated these configurations for use with the 12-meter trusses. The truss was also to be used to test the counterbalance suspension concept.

The testbed truss was fabricated from polyvinyl chloride (PVC) tubing and assembled in the FIBG large acoustic chamber cantilevered from the floor as shown in Figure 5. A scaffolding was erected to provide access to the truss for instrumentation. Limited dynamic analysis and testing were performed. The truss was never cantilevered from the ceiling or used with the counterbalance suspension. These tasks were dropped from the program in favor of the 12-meter trusses. The primary benefit of the Testbed Truss experiment was the scaffolding fabricated for it which was later used for the 12-meter trusses.

12-Meter Trusses--The 12-meter trusses were a pair of 12-meter long aluminum and plastic truss beams used as test articles to evaluate ground test methods and passive and active vibration control in the LSSTP. One of the trusses had low inherent modal damping representative of future LSS while the other had significant damping designed into it using viscoelastic materials. The two trusses evolved from the Phase III, 40-foot truss of the original LSSTP project plan and from the "twin tower" trusses on the PACOSS contract. The 40-foot truss was to have been a testbed for passive/active control experiments and for ground test methods development. The 12-meter trusses filled these requirements while also providing a direct comparison of the benefits of passive damping. The "12-meter" designation came from the planned 1/5-scale model of the NASA COFS Mast truss, which was 60 meters in length.

The 12-meter trusses were the workhorses of the LSSTP. They were tested in vertical cantilever and horizontal soft suspension configurations; the undamped truss was tested in a microgravity environment on board a NASA KC-135 aircraft performing parabolic arc flight maneuvers; and the undamped truss was fitted with active control hardware for the 12-Meter Truss Active Control Experiment. The ground and flight tests are discussed later in this section. The active control experiment is discussed in Section 4, Active Vibration Control.

The 12-meter trusses were a pair of slender truss beams each 12 meters long with welded tubular aluminum alloy frames and a 20 inch square cross section. Each truss had four bolt-together sections with four truss bays per section for a total of 16 bays. One of the trusses was designed to have low modal damping in the low frequency bending and torsion modes. This was achieved by using low loss Lexan tubing for the bolt-in diagonal members. The other truss was designed to have significant damping in the low frequency modes by incorporating a viscoelastic axial damper in the diagonal members. The trusses are shown in a vertical cantilever configuration in Figure 6.

Each truss was tested in a vertical cantilever configuration to determine modal parameters. The undamped truss is shown in the vertical test configuration in Figure 7. Excitation was provided by a single electromagnetic shaker suspended from the scaffolding near the mid-span of each truss. The measured frequencies for the undamped truss agreed well with finite element predictions. The damped truss results were not as good, however. Measured bending frequencies agreed with predictions reasonably well, but measured damping ratios in the bending modes were lower than predictions.

Furthermore, no torsion modes could be experimentally identified due to the high damping present. Details of the vertical cantilever tests can be found in [9] and [10].

The undamped 12-meter truss was also tested in a horizontal configuration suspended from a soft suspension system to simulate zero gravity. The suspension system used three zero-rate spring mechanisms (ZSRMs) to provide a low suspension stiffness in the vertical direction. The horizontal test configuration of the truss is shown in Figure 8. The ZSRM design, which had been used previously on the PACOSS program, employs mechanical springs and levers to obtain a soft spring with no net static deflection. The low suspension stiffness uncoupled the structural modes from the low frequency suspension modes. The truss was suspended on cables from the ZSRMs so that the pendulum effect of the cables isolated the horizontal plane bending modes. Modal test results from the horizontal configuration agreed well with finite element predictions for the torsion modes and horizontal plane bending modes. However, the vertical plane bending modes were coupled with truss cross-section deformation modes by friction in the ZSRMs. The friction also increased the damping of the vertical plane bending modes significantly. The horizontal test results and the ZSRMs are described in detail in [11].

12-Meter Truss Zero-G Flight Test--The undamped 12-meter truss was tested in a microgravity environment to compare with the horizontal free-free ground test. The test was proposed by Capt George Studor as part of his reserve officer assignment with the Structures Division. The testing was done aboard a KC-135 aircraft operated by the NASA Lyndon B. Johnson Space Center (JSC) for reduced gravity testing. The aircraft flies parabolic arc trajectories which provide up to 25 seconds of microgravity test time as the test object "floats" inside the aircraft cargo bay. A Memorandum of Understanding was arranged with the JSC Reduced Gravity Office to provide support for the test. A 2 meter long truss was tested in the aircraft prior to the 12-meter truss to help define the dynamic environment and aid in test planning. Figure 9 shows the 2-meter truss in the cargo bay during a flight. The 2-meter truss test verified the basic approach for the large truss test, but test times of only 8 to 10 seconds were achieved instead of the 25 seconds anticipated. This was due to small variations in the aircraft trajectory which caused the truss to "float" into the fuselage floor or wall. The 12-meter truss test was flown successfully in February 1990. Figure 10 shows the truss in the aircraft during a test. Shortly after the flight it was discovered that one of the truss diagonal members was loose. Thus, the flight test data were not comparable with previous ground test results.

To solve this problem, a second ground test was performed, with the member loose, resulting in good agreement with the flight test. The data analysis of the short-time-record flight data and comparison with ground tests is described in [12]. The flight test effort is described in detail in [13]. During the flight test an active member actuator developed by the Jet Propulsion Laboratory was tested on the truss. More information on the active member development is available in [14].

4.0 ACTIVE VIBRATION CONTROL

Active Vibration Control was the second area of emphasis in the LSSTP, the first being the ground testing and zero-gravity simulation discussed in Section 3. This section describes the active vibration control experiments conducted under the LSSTP including the Cantilevered Beam, Tetrahedral Truss, Advanced Beam and 12-Meter Truss.

Cantilevered Beam--The Cantilevered Beam was the first active vibration control experiment completed under the LSSTP. The experiment began before the start of the LSSTP and became a part of the project. The experiment consisted of a 1.0 inch by 6.0 inch by 60 inch long aluminum beam cantilevered in a horizontal plane. Two electromagnetic shakers were used to apply forces to the beam; one for active control forces and the other for disturbances. Beam motion was sensed by two linear variable differential transformers (LVDTs). The beam test configuration is shown in Figure 11. Active controller implementation was provided by a Systolic Systems PC-1000 real-time control computer. Some success was achieved in closed-loop control of the first bending mode of the beam, but beam hardware problems, including an inadequate root clamping fixture, limited the usefulness of the experiment. The cantilevered beam experiment was more useful as a learning experience for future active control experiments. A description of the Cantilevered Beam experiment can be found in [15].

Tetrahedral Truss--The Tetrahedral Truss experiment was planned as the first active control experiment under the LSSTP. The truss was to duplicate as closely as possible the ACOSS model no. 1 structure which had been used extensively under the ACOSS program for analytical vibration control studies [1]. The structure was simple: a tetrahedral truss with 6 axial members. However, fabricating a physical model of the truss proved to be very difficult. The model used under ACOSS was given unit dimensions for simplicity, but these dimensions were not reasonable for a physical structure. Designing pinned joints for the truss was also very difficult. As a result of these problems, the Tetrahedral Truss experiment was dropped from the program after several months of frustrating design work in favor of a simpler experiment, the Advanced Beam.

Advanced Beam Experiment--The Advanced Beam Experiment was born out of the search for a simple active control experiment to replace the Tetrahedral Truss. The design had to meet a few basic requirements of LSS: lowest frequency below 5 Hz, multiple modes which could be coupled, and inertial sensors and actuators. The experiment configuration selected was a slender aluminum beam oriented vertically and cantilevered at the top end. The beam was 71 inches long with a rectangular cross section of 0.75 inches by 1.0 inches. A 12 inch diameter, 1 inch thick aluminum disk was attached to the beam's free end to reduce the fundamental torsion mode frequency and to provide a mounting location for actuators. The design had two bending modes and one torsion mode below 15 Hz. Four linear momentum exchange (proof mass) actuators of the VCOSS II design [16] were arranged in two pairs on the end disk, one pair aligned with each bending axis. Each pair could be commanded in-phase to control bending while either or both pairs could be commanded out-of-phase to control torsional motion. Control sensing was accomplished by four small accelerometers, one collocated with each actuator. The acceleration signals were integrated in analog circuitry to produce the velocity signals for control. Real-time feedback control was implemented with the PC-1000 control computer. The Advanced Beam Experiment configuration is shown in Figure 12.

Much effort was expended developing the hardware for the Advanced Beam experiment, especially the actuators. Wayne Yuen performed much of the actuator development and open-loop characterization of the experiment [17] [18]. Professors Ozguner and Yurkovich and their graduate students from the Ohio State University provided considerable support, including development of the experimental hardware and design and testing of active control approaches. In addition, Capt Tom Cristler, a graduate student at the Air Force Institute of Technology (AFIT), was instrumental in developing the experiment.

The Advanced Beam Experiment was a valuable learning experience in the design of LSS control experiments. A well characterized system was achieved. Open-loop test data agreed reasonably well with the initial finite element model. However, the model was improved to make fundamental bending and torsion frequencies match test results more closely. The biggest limitation of the experiment was the actuators. The VCOSS II actuator design had excessive friction and a reduced force constant due to the arrangement of the shaft and linear bearings. Analog compensation circuitry designed to "tame" the actuator dynamics improved their performance somewhat, but a better actuator design would have been useful. The experiment also suffered from the actuator's limited proof mass travel, a fundamental weakness of linear momentum exchange actuators at low frequencies. Although the actuator had a maximum force output of 4.0 pounds, it could only develop this at frequencies above 10 Hz. As a result, only 0.1 pounds of force was available at the lowest beam frequency of 1.3 Hz. The large mass of the actuators relative to the mass of the beam was also a problem. The significant mass at the beam tip caused a node to occur there for all bending modes higher than the fundamental pair. Thus, useful control authority was limited to the two fundamental bending modes and the first torsion mode.

Several controllers were designed and implemented on the Advanced Beam Experiment by Ohio State and AFIT investigators. Both centralized and decentralized designs were studied. Closed-loop damping ratios exceeding 10% of critical were measured. Although higher damping ratios were desired, 10% was reasonable given the low actuator output at low frequencies, discussed above. The Ohio State work is described in [19] and [20]. The work performed by Capt Cristler of AFIT in support of the experiment is described in [21].

<u>12-Meter Truss Active Control Experiment</u>--The 12-Meter Truss Active Control Experiment was the last and most complex active vibration control experiment performed under the LSSTP. The primary objective of the experiment was to evaluate the performance of state-of-the-art active vibration control approaches on a realistic structure possessing dynamic response and control hardware characteristics representative of future space systems. A second objective was to evaluate the performance of a new real-time digital control computer for simultaneous closed-loop vibration control, data acquisition and overall experiment control.

The primary design goal of the experiment was to include structural dynamic characteristics which would be common to many future large flexible space structures. These characteristics included a truss structure with a lowest natural frequency at or below 1 Hz, high modal density at low frequencies and modal damping ratios of less than 1% of critical in global, low frequency modes. Second, it was important to use non-grounded control sensors and actuators. In addition, it was important that the experiment have a directly measurable figure of merit indicative of system performance. This figure of merit would be used as the control design objective and to directly measure experimental closed-loop performance. Finally, it was desirable to have an unconstrained structure to at least partially simulate the zero-gravity environment of space.

The undamped 12-meter truss was the logical choice for the basic structure of the experiment. The horizontal soft suspension configuration was considered first since it had more realistic boundary conditions, but the lowest truss frequency was above 10 Hz, which was too high. In the vertical cantilever configuration with the additional mass of actuators, the truss would have a lowest mode frequency under 2 Hz and five modes below 10 Hz. The existing finite element models and modal data for the trusses would mean a savings in the analysis and test time required to develop the experiment. A performance figure of merit was chosen as the horizontal plane displacement of a point light source offset to one side of the truss tip. This figure of merit had contributions from lower frequency bending and torsion modes and could be directly measured by an optical sensor mounted at the base of the truss.

The undamped truss was fitted with eight momentum exchange actuators based on the PACOSS design [22]. Two symmetric pairs of actuators were located at the truss tip to provide both bending and torsion control. These locations provided good observability and controllability for all the modes to be controlled except the third bending mode pair. In addition, pairs of actuators were located on the truss neutral axis in both bending directions at the 1/2 and 3/4 stations. These actuators were to provide additional control authority for the bending mode pairs. Sensing was accomplished by a piezoelectric accelerometer collocated with each actuator. The acceleration signal was converted to velocity by an analog integrator. Real-time control was accomplished by a Systolic Systems Optima digital control computer system. The system features a VME-based real-time controller with 12 channels of analog input and output linked to a Sun Microsystems Unix workstation for controller design and development. In addition to real-time control, the Optima system was used for data acquisition and analysis, disturbance signal generation and overall experiment timing. The Optima system is discussed in more detail in Section 5. An additional actuator was placed at the truss tip, offset to one side, to provide disturbance forces to both bending and torsion modes. Later, an electromagnetic shaker was installed at the truss tip to provide larger disturbance forces. The 12-Meter Truss Active Control Experiment configuration is shown in Figure 13. The overall active control system is shown schematically in Figure 14.

The open-loop dynamic characteristics of the control configured truss were thoroughly evaluated. Dynamic test results agreed well with finite element model predictions. Measured frequencies closely matched predictions, which was expected since the model had been corrected based on bare truss test results. Measured modal damping ratios were higher than expected, especially in the fundamental x and y-axis bending modes. This was primarily attributed to Coulomb friction in the actuator linear bearings. A method for identifying this friction was developed and is presented in [23]. A complete description of the design and open-loop testing of the experiment can be found in [24].

Active controllers for the 12-meter truss were designed by Ohio State University investigators with two control objectives in mind. The first objective was to generally increase passive damping in all controlled modes. This included the lowest 4 truss bending modes and the lowest torsion mode. The second objective was more typical of a real system: minimize the truss tip displacement as measured by the optical sensor. The first objective weighted all controlled modes as equally important while the second considered only those modes which affect truss tip motion: primarily the first bending modes with some reduced emphasis on first torsion and second bending. Both centralized and decentralized controller designs were accomplished. All designs were based on linear quadratic regulator theory. Several controllers of each type were designed using direct output feedback and full state feedback.

The 12-Meter Truss Active Control Experiment was a good test bed for evaluating active control design approaches. Most of the active control approaches implemented on the truss achieved significant closed-loop damping increases. The controllers were generally most effective at adding damping to the fundamental x and y-axis bending modes. This was expected since these two modes dominated the tip displacement figure-of-merit response. The best centralized and decentralized controllers achieved more than a 40% reduction in the rms displacement of the tip light source to a random disturbance. Details of the decentralized controller design can be found in [25]. A complete account of the Ohio State control activity for the truss is presented in [26].

5.0 FACILITY AND EQUIPMENT IMPROVEMENTS

The LSSTP provided several improvements in facilities and equipment to the Structures Division. These improvements are described briefly in this section.

Vibration Test Facilities--A large, climate-controlled test enclosure and a smaller control room were purchased and used under the LSSTP. The 30 ft by 30 ft by 40 ft tall test enclosure was purchased to house the 12-Meter Truss Active Control Experiment and the PACOSS Dynamic Test Article. The enclosure provided a clean, secure, temperature controlled environment for testing. The temperature control was a necessity to ensure constant temperature in the viscoelastic damping materials. The 12 ft by 16 ft control room was purchased in 1988 to provide a clean, air-conditioned area for housing a modal data acquisition system. The modal system was used to perform modal tests on the 12-meter trusses in vertical cantilever and horizontal free-free configurations.

Optima Control Computer--The Optima real-time control computer system used on the 12 Meter Truss Active Control Experiment was developed and purchased under the LSSTP. A study was performed by Systems Engineering Concepts, Inc. to define a next generation control computer architecture which would allow remote control execution of experiments in the laboratory in the same way in which they would be run on-orbit. A system meeting these requirements was then purchased from Systolic Systems, Inc. The system has two major components: the development system and the real-time controller. The development system, a Sun Microsystems graphics workstation, is used for software development, simulation, downloading of control code to the controller and analysis of test data. The real-time controller is a VME-based computer with a fast host processor, 12 channels of 16 bit analog input and output, a high speed vector processor and 4 Mbytes of memory for code and data storage. The Optima system provided real-time control code execution as well as data acquisition and disturbance signal generation. The controller is fully programmable in the C language, which allows a wide range of nonlinear or time varying control laws with concurrent sampling and storage of desired time histories.

Motion Analysis System--Early in the program, a video-based motion analysis system was acquired to measure displacements of experimental structures without the need for sensors on the structure. The system consisted of a video camera and computer-based image processor that tracked and computed the planar motion of several target points on a structure. The system works by placing reflective targets on a structure to be measured and video-taping the structure in motion. The video tape is then played back off-line into the image processor and the planar displacements of the targets are computed and stored. The system was used extensively with the early counterbalanced suspension tests and with the 2-meter truss onboard the NASA Reduced Gravity KC-135 aircraft in preparation for the 12-Meter Truss Zero-G Flight Test.

Zonic Modal Test System--The LSSTP provided partial funding in the purchase of a Zonic modal test system. The system has 64 channels and is controlled by a DEC workstation. The system was to have been used primarily for modal testing of the PACOSS Dynamic Test Article. The DTA was subsequently dropped from the program, however. The Zonic system was used for later modal tests on the 12-meter trusses and has been used extensively on system support efforts.

Linear Momentum Exchange Actuators--Much effort was expended under the LSSTP to develop and characterize the linear momentum exchange actuators and their drive circuitry for the 12-meter truss active control experiment. The final actuator configuration performed very well. Nine actuator systems were fabricated and used on the truss. The actuator represented the state-of-the-art in linear momentum exchange actuators for low frequency applications. In addition, the current drive and analog integration circuits for the actuators performed well and have been used for other dynamic test applications.

6.0 CONCLUSIONS

The Large Space Structures Technology Program was successful in establishing a significant base of experience in the Structures Division in applied dynamics and control of large space structures. The LSSTP was a large, ambitious project. The resources expended in funds and personnel for an in-house project were significant. These resources were even more significant since the program was undertaken by an organization that primarily performed contracted research. The focus of the program on space structures, in an organization devoted primarily to airplanes, made its succe'ses even more impressive. In addition to its successes, the program also had some disappointments. This sections presents some conclusions of the 6-year project.

The LSSTP was begun in 1985 with much enthusiasm and management support. The scope of the project was large, encompassing nearly all areas of structural dynamics for space structures. The personnel assigned to the program at its inception were eager but inexperienced. This lack of experience caused problems throughout the program; there were too few experienced people and too much work to be done. As a result, experiment schedules were lengthened and some were even dropped. This effect can be seen by comparing the initial and actual program schedules shown in Figures 1 and 2, respectively. The cancellation of the NASA COFS project, to which LSSTP tasks were directly dependent, caused more problems in the schedule. Eventually, the work planned shrank to fit the available resources. However, the work could have been performed more efficiently if a more focused scope and realistic assessment of personnel qualifications were considered from the outset.

The emphasis of the LSSTP was on experimentation. To that end, several experiments were developed and performed. The experiments were directed toward two technology areas; ground based testing to simulate the zero-gravity environment of space and active vibration control. Ground testing experiments began with the Testbed Truss and the Counterbalance Suspension and progressed to the 12-meter trusses and a reduced gravity flight test. Active vibration control experiments evolved from the simple Cantilevered Beam to the Advanced Beam and finally to the 12-Meter Truss Active Control Experiment.

The ground testing work on the counterbalance suspension ultimately proved the concept impractical, but exposed the investigators to the challenges of testing low frequency, unconstrained structures. New equipment and test techniques were acquired and developed. The motion analysis system was very useful in measuring the large, low frequency motion of structures without the need for sensors mounted on the structure. The zero spring-rate mechanisms investigated later in the program were more practical than the counterbalance approach but they also had significant limitations. Friction in the linear bearings and shafts of these mechanical devices made them undesirable for use with low mass, higher frequency structures. The zero-g flight test of the 12-meter truss in the NASA reduced gravity aircraft was a success, but presented challenges in instrumentation and modal identification from short data records.

The active vibration control experiments, beginning with the Cantilevered Beam, made the realities of modelling errors, nonlinearities, and sensor and actuators dynamics painfully obvious. Development of sensor and actuator systems was a challenge throughout the program. The Tetrahedral Truss experiment illustrated the problems in scaling a theoretical structure into real hardware. The Advanced Beam Experiment was a useful testbed for active control, but it had considerable limitations in sensors and actuators. The 12-Meter Truss Active Control Experiment took over a year to develop, but was a very good test bed for identification and active controller evaluation. The Ohio State University investigators designed more than 30 controllers for the truss. Some performed very well; others graphically illustrated the reality of instabilities.

The new facilities and equipment described in Section 5 provide a continuing benefit to the Air Force. The large test enclosure and control room were used for many tests under the LSSTP and will continue to be used in the future. The Optima control computer was very useful in to the 12-Meter Truss Active Control Experiment, providing real-time control as well as data acquisition and overall experiment control in a single package. The Zonic modal test system continues to be a workhorse for large modal tests.

Even though the LSSTP emphasized experimental research and development, the need for dynamic analysis was large. Analysis needs ranged from predicting dynamic response of test articles and suspension systems to active control design and simulation to modelling of actuator dynamics. A useful finite element analysis capability was developed in the Structural Dynamics Branch using the PC based MSC PAL2 code. The tool was used to design and analyze the Advanced Beam, counterbalance suspension concepts, and the 12-meter trusses. It was also used to estimate the modal damping in the damped 12-meter truss using the modal strain energy (MSE) technique. State space modelling methods were also used for the Advanced Beam Experiment and the 12-Meter Truss Active Control Experiment using Matlab software.

In summary, the LSSTP was a success in establishing a significant base of experience in the Structures Division in applied dynamics and active control of space structures. The project focused on experiments, and several were sucessfully developed and performed in the areas of ground testing and active vibration control. The LSSTP also provided improvements to facilities and equipment in the Structures Division which will be used on future projects. Finally, even though Wright Laboratory has dropped the mission area of space, the experience base gained through the LSSTP will continue to benefit the Air Force in applications to advanced aircraft and aerospace vehicles.

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Table 1. LSSTP Participants

Name	Position	Organization
Jerome Pearson	project manager	FIBG
Terry Hertz	deputy manager	FIBR
Maj Alan Janiszewski	project manager	FIBG
Bob Gordon	project manager/deputy	FIBA/FIBG
Capt Mark Arnold	engineer	FIBG
Kevin Harris	engineer	FIBG
Doug Henderson	engineer	FIBG
Joe Hollkamp	engineer	FIBG
Gene Maddux	engineer	FIBG
Arnel Pacia	engineer	FIBG
Capt Andy Swanson	engineer	FIBG
Capt Jim Williams	engineer	FIBG
Wayne Yuen	engineer	FIBG
Capt Mike Zeigler	engineer	FIBG
Mike Banford	technician	FIBG
Mike Hart	technician	FIBG
Earl Rogers	technician	FIBG
Sam Pollock	engineer	FIBA
Lynn Rogers	engineer	FIBA/FIBG
Harold Croop	engineer	FIBC
Mike Camden	engineer	FIBE
Capt Craig Parry	engineer	FIBR
Capt Bruce Snyder	engineer	FIBR
Larry Kretz	engineer	FIBT
Tim Sikora	engineer	FIBT
Capt Kristen Farry	engineer	FIGC
Capt Ken Elkins	engineer	FIGC
Capt Sharon Heise	engineer	FIGC
Maj George Studor	engineer	AF Reserve

Table 1. LSSTP Participants (cont)

Name	Position	Organization
Don Mittleman	professor	Oberlin College
Umit Ozguner	professor	Ohio State
Steve Yurkovich	professor	Ohio State
Eric Breitfeller	grad student	Ohio State
Anne Bruner	grad student	Ohio State
Peter Dix	grad student	Ohio State
Layne Lenning	grad student	Ohio State
Capt Tom Cristler	grad student	AFIT
Capt Michelle Gaudreault	grad student	AFIT
Chuck Gendrich	grad student	Michigan State
Jenny Huston	grad student	Ohio University
Vincent Ree	grad student	RPI
Cliff Zaretsky	grad student	RPI
Trey Fuller	cadet	AF Academy
Steve Guerney	cadet	AF Academy
Stacey Nelson	cadet	AF Academy
Mike Rickard	cadet	AF Academy
Mike Sheperd	cadet	AF Academy
Pat Weir	cadet	AF Academy

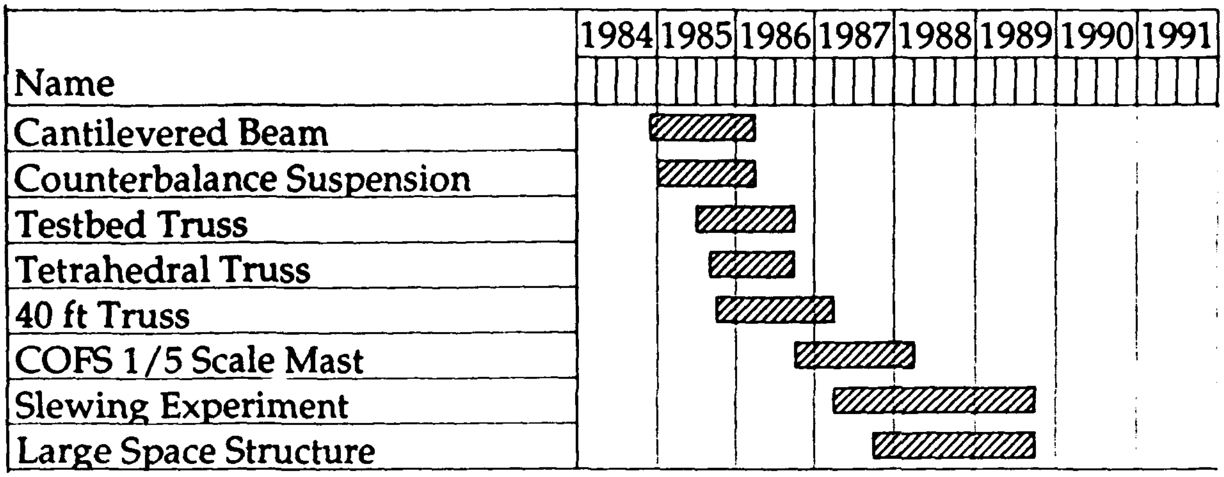

Figure 1. Original LSSTP Program Schedule

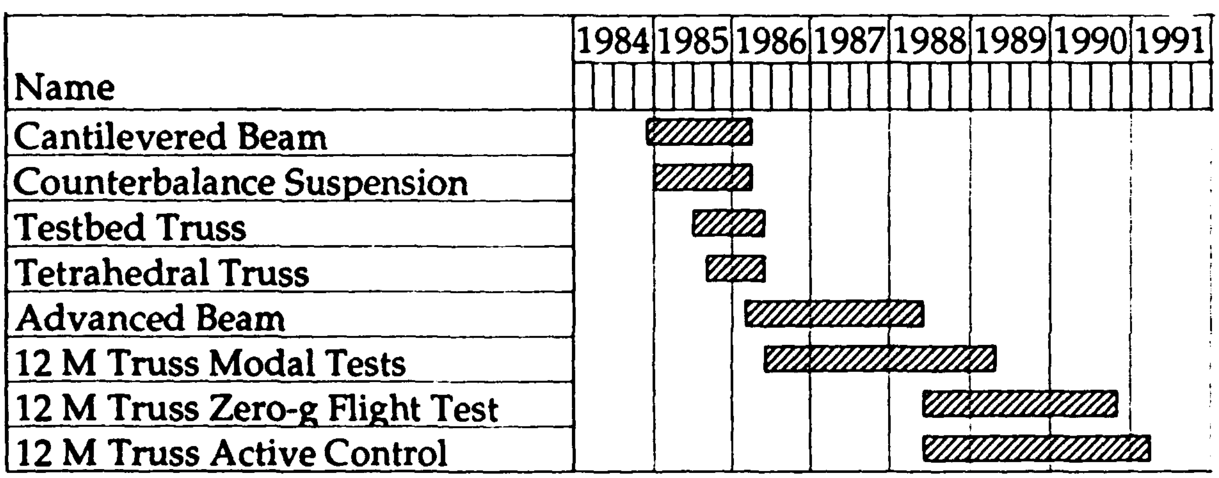

Figure 2. Actual LSSTP Program Schedule

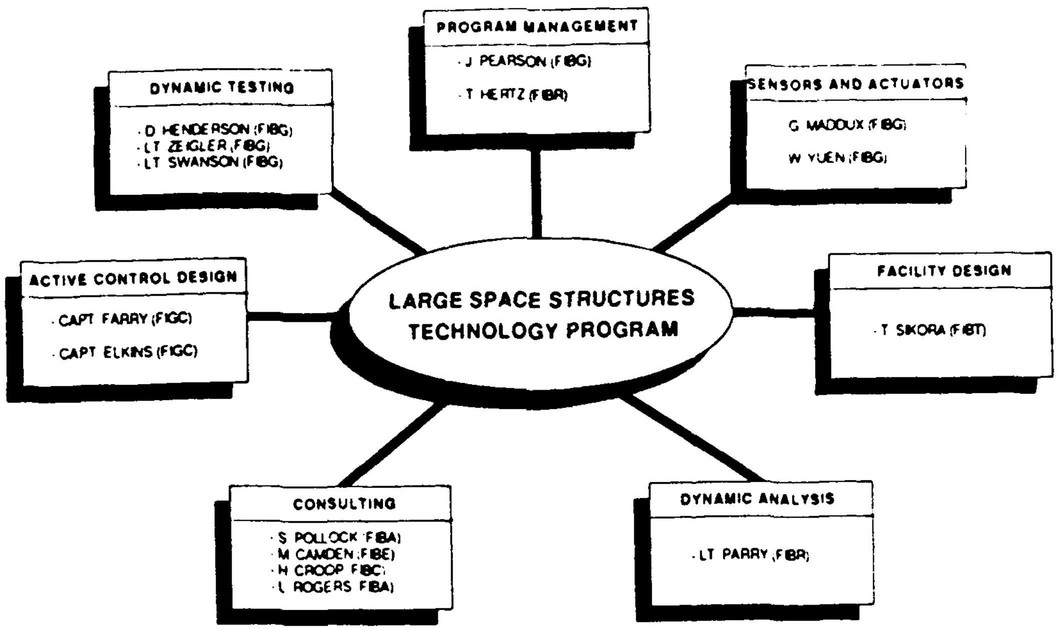

Figure 3. The LSSTP Team

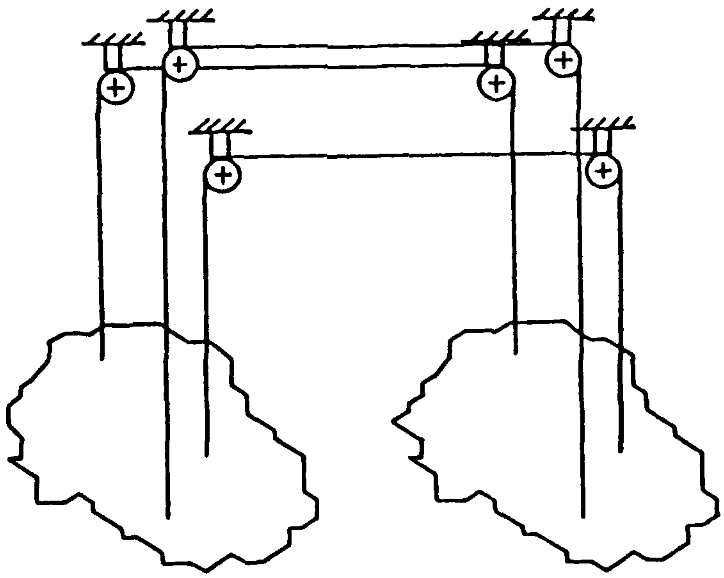

Figure 4. Counterbalance Suspension Concept

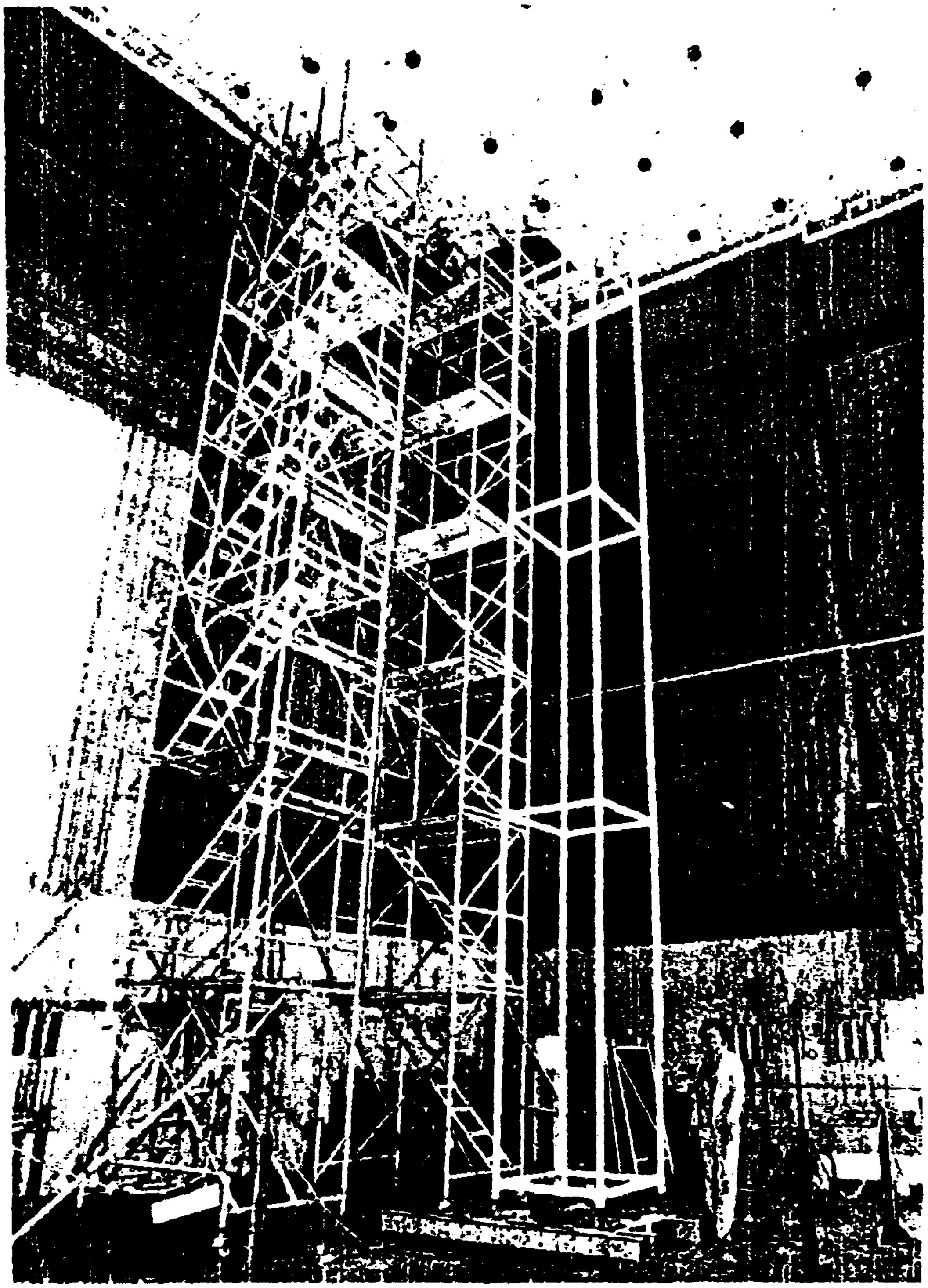

Figure 5. Testbed Truss

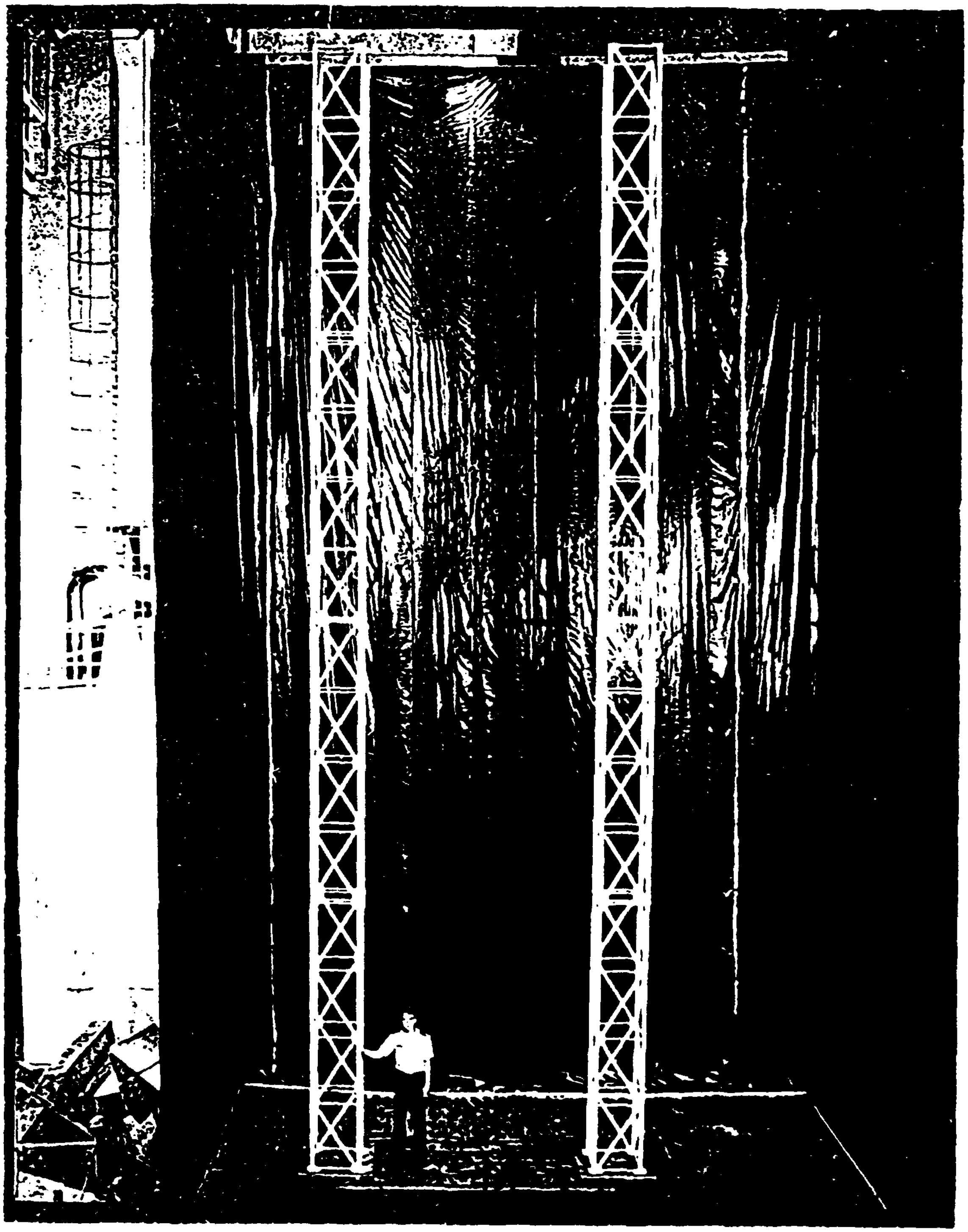

Figure 6. The 12 Meter Trusses

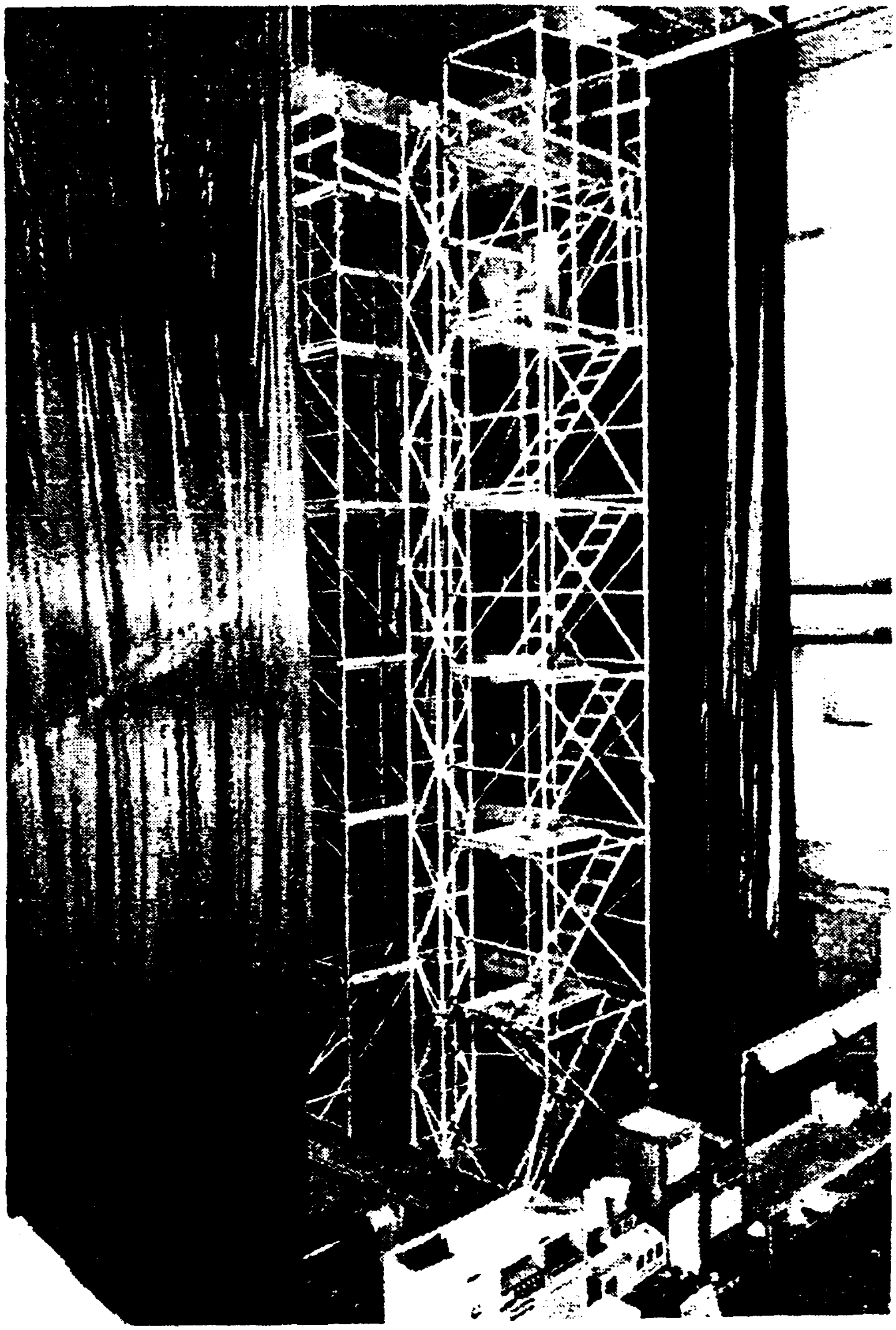

Figure 7. Vertical Cantilever Test of the Undamped 12-Meter Truss

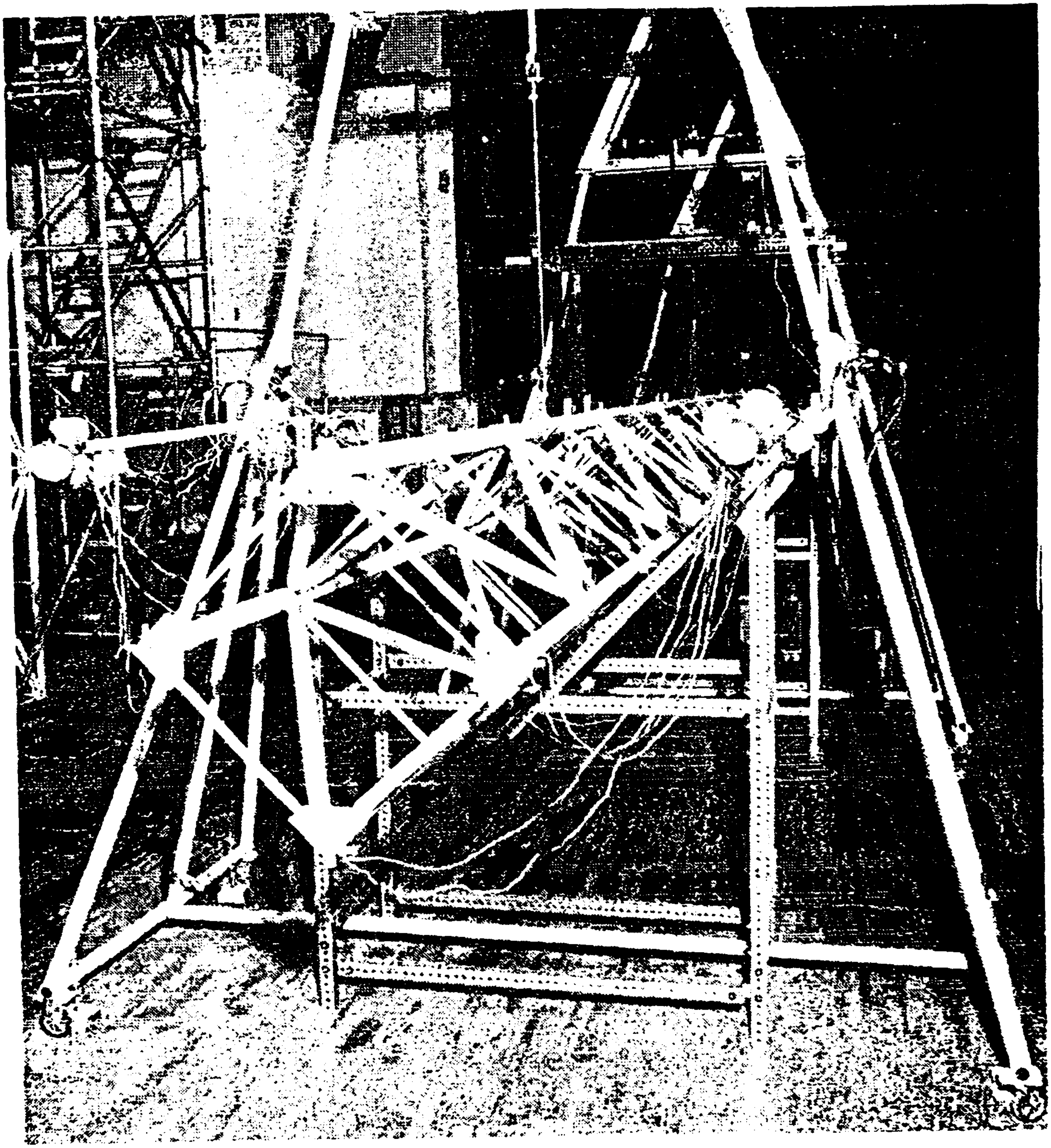

Figure 8. Horizontal Test of the Undamped 12-Meter Truss

Figure 9. 2-Meter Truss in NASA Reduced Gravity Aircraft

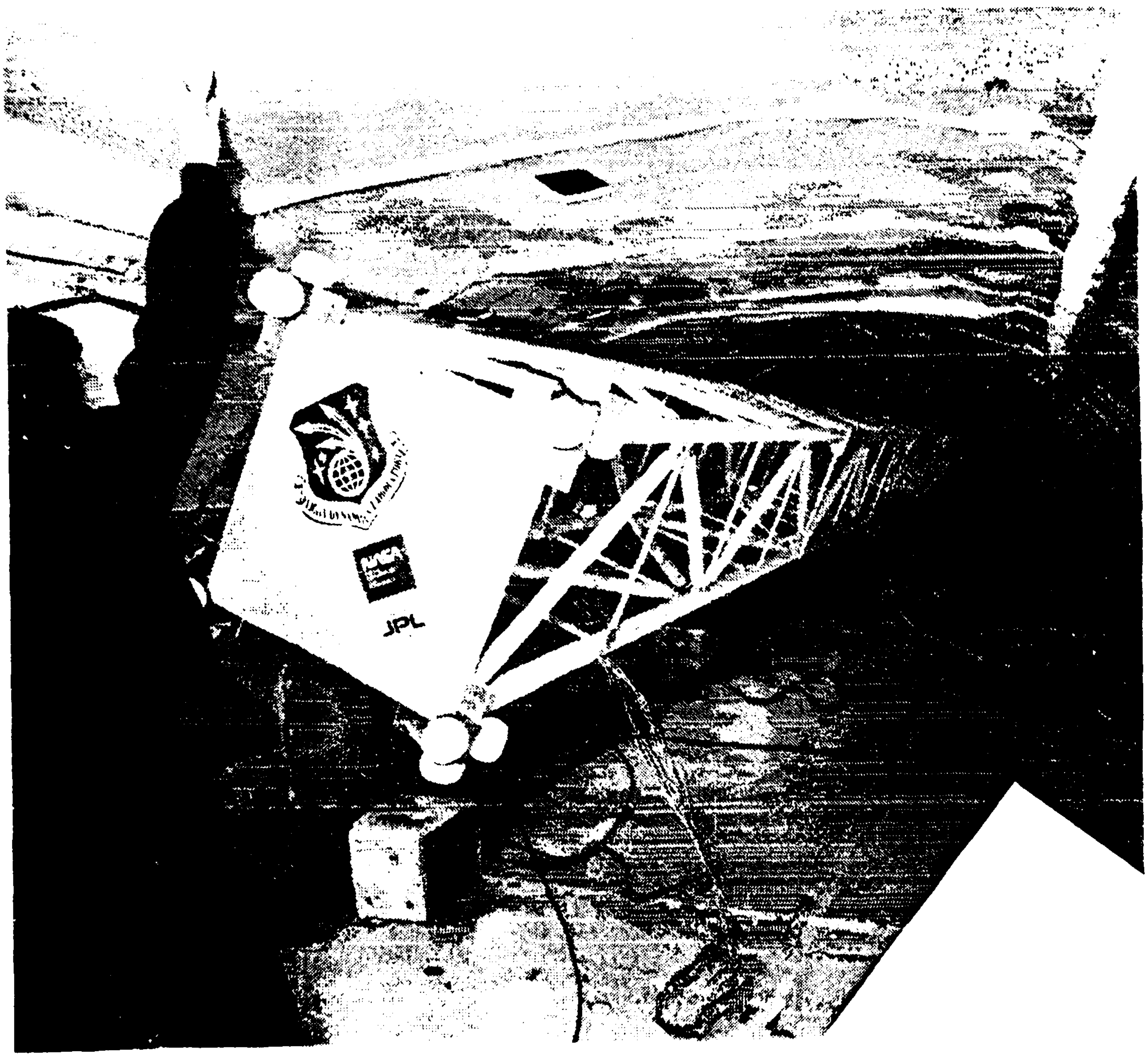

Figure 10. 12-Meter Truss in the NASA Reduced Gravity Aircraft

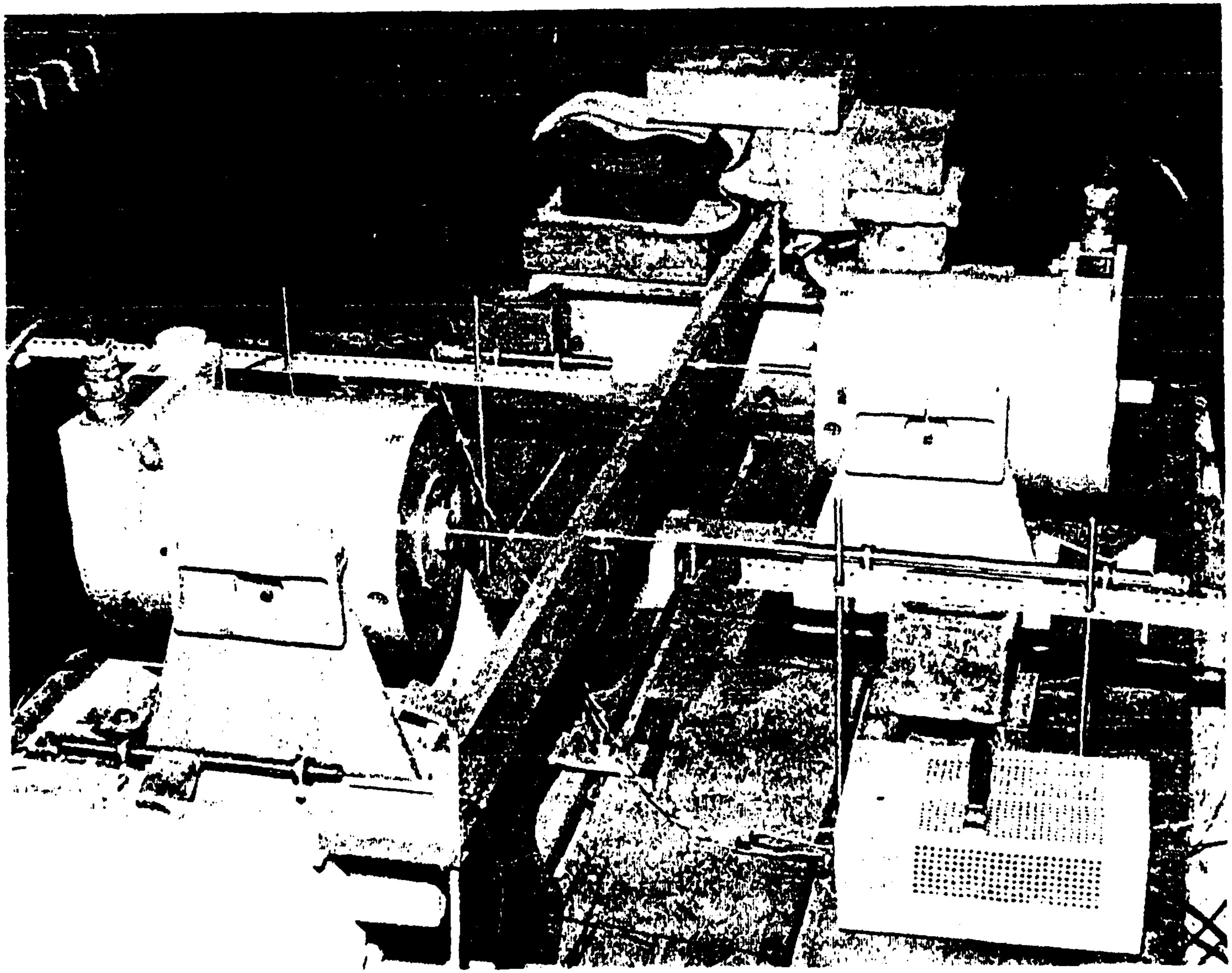

Figure 11. Cantilevered Beam Experiment Configuration

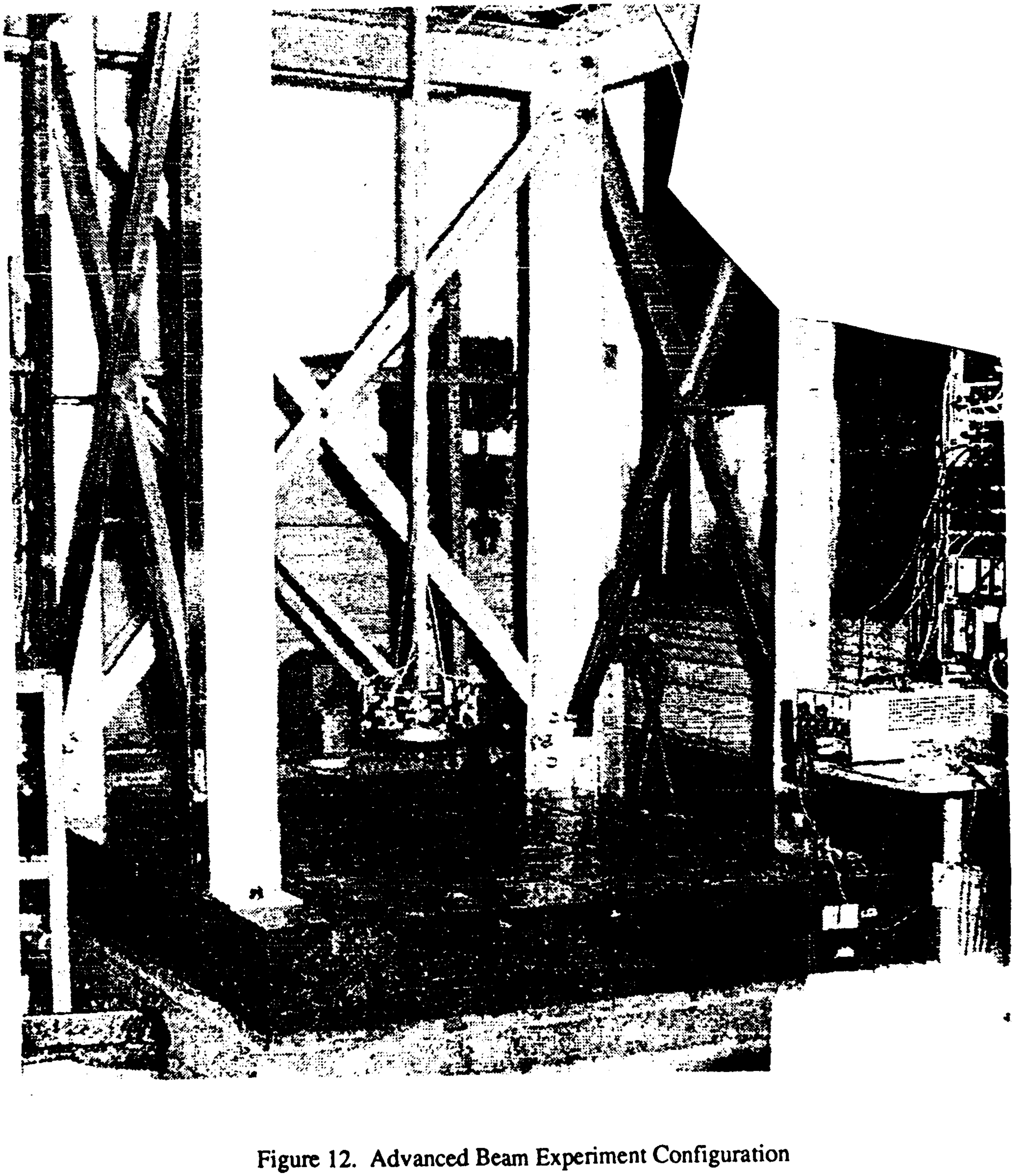

Figure 12. Advanced Beam Experiment Configuration

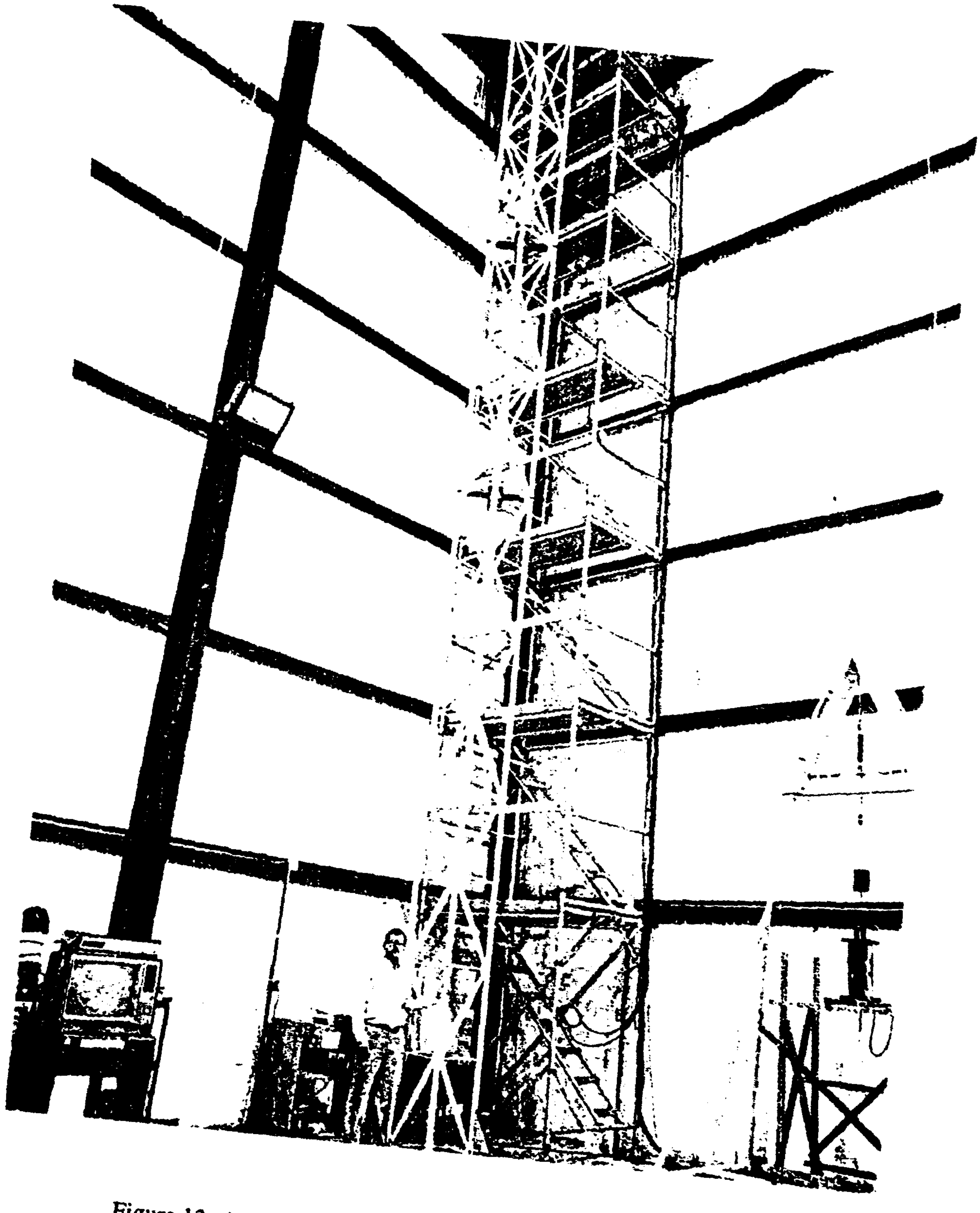

Figure 13. 12-Meter Truss Active Control Experiment Configuration

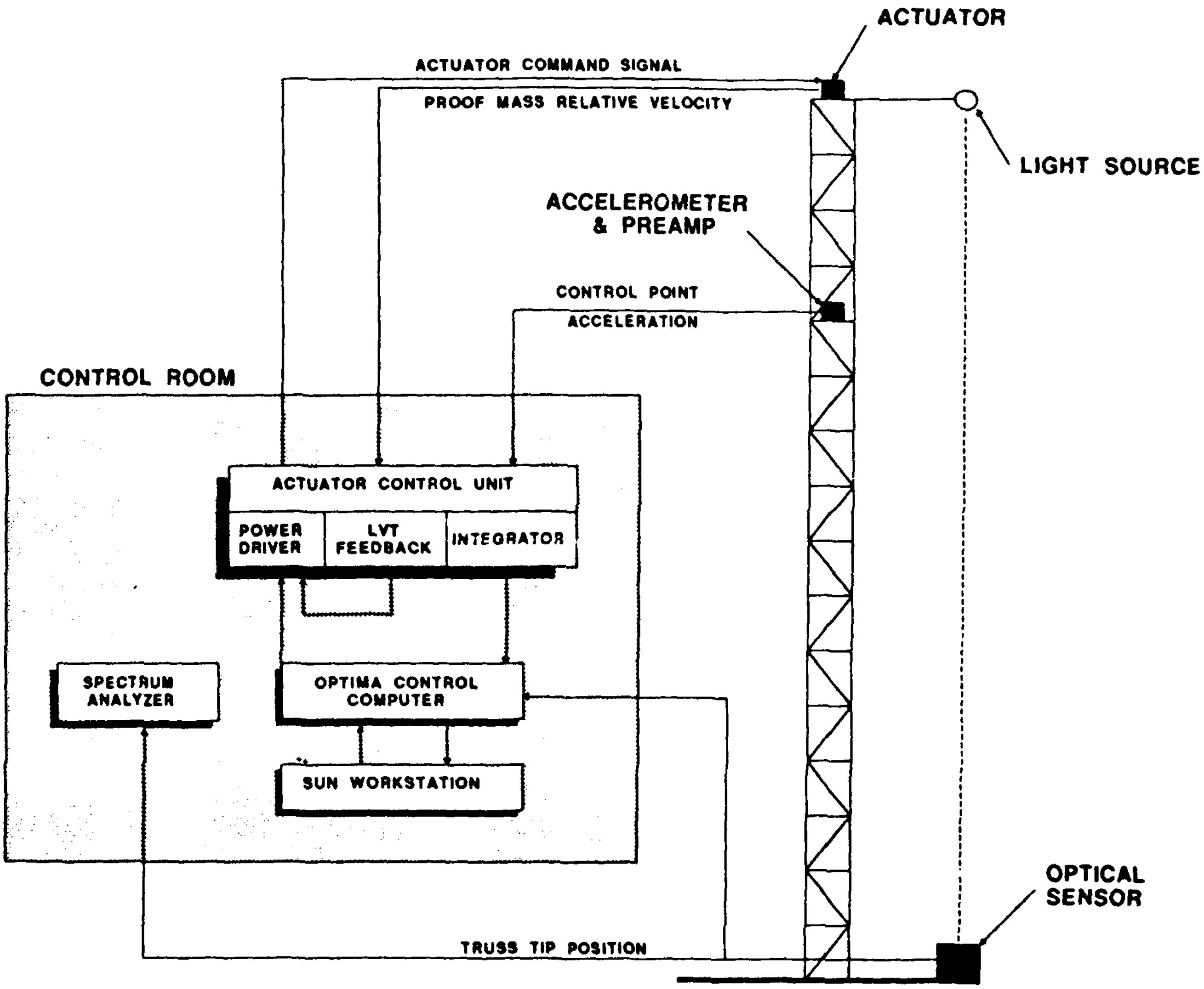

Figure 14. Schematic Diagram of the 12-Meter Truss Active Control Experiment

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